R-PARITY VIOLATION AND NEUTRINO MASSES

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R-parity violation in the supersymmetric standard model could be the origin of neutrino masses and mixing accounting for the atmospheric and solar neutrino oscillations. More interestingly, this hypothesis may be tested in future colliders by detecting lepton number violating decays of the lightest supersymmetric particle. Here, we present a comprehensive analysis for the determination of sneutrino vacuum expectation values from the one-loop effective scalar potential, and also for the one-loop renormalization of neutrino masses and mixing. Applying our results to theories with gauge mediated supersymmetry breaking, we discuss the effects of the one-loop corrections and how the realistic neutrino mass matrices arise.

The minimal supersymmetric standard model (MSSM) may allow for explicit lepton number and thus R-parity violation through which neutrinos get nonzero masses [1]. As it is an attractive possibility to explain the neutrino mass matrix consistent with the current data coming from, in particular, the atmospheric [2] and solar neutrino [3] experiments, many works have been devoted to investigating the properties of neutrino masses and mixing arising from R-parity violation [see references in [4]]. The lepton number and R-parity violating terms in the MSSM superpotential are

$$W = \mu_i L_i H_2 + \lambda_{ijk} L_i L_j E^c_k + \lambda'_{ijk} L_i Q_j D^c_k \,. \tag{1}$$

We first recall that there are two contributions to neutrino masses from R-parity violation. One is the loop mass arising from one-loop diagrams with the exchange of squarks, sleptons or gauginos. The other is the tree mass arising from the misalignment of the bilinear couplings in the superpotential and sneutrino vacuum expectation values (VEVs) determined by the minimization of the scalar potential,

$$V = [(m^2_{L_i H_1} + \mu\mu_i) L_i H_1^\dagger + B_i L_i H_2 + \text{h.c.}] + m^2_{L_i} |L_i|^2 + V_D + \cdots \,. \tag{2}$$

Here $m^2_{L_i H_1}$, B_i and $m^2_{L_i}$ are the soft terms, μ is the supersymmetric Higgs mass parameter, and V_D denotes the SU(2)xU(1) D-terms.

The first attempt to investigate whether R-parity violation can provide the solution to the atmospheric and solar neutrino problems has been made in [5], where it was found that the minimal supergravity model with bilinear R-parity violating terms naturally yields the desired neutrino masses and

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mixing angles. According to the scatter plot study of minimal supergravity parameter space [5], the matter conversion (vacuum oscillation) solution to the solar neutrino problem was found to be realized in a few % (20 %) of the selected parameter space. After the observation of muon neutrino oscillation in Super-Kamiokande [2], the similar attempt has been made in the context of minimal supergravity models with generic (trilinear) R-parity violating couplings [6] to find out the preferred ranges of the soft parameters depending on $\tan\beta$, and to obtain the correlation between the neutrino properties (the atmospheric mixing angle and the ratio between two heaviest masses) and the soft parameters.

A remarkable feature of R-parity violation as the origin of neutrino masses and mixing is that this idea can be tested in future collider experiments despite the small R-parity violating couplings. For instance, the large mixing angle between the muon and tau neutrino [2] implies the observation of comparable numbers of muons and taus produced in the decays of the lightest supersymmetric particle (LSP) [7]. Moreover, the factorization of the R-parity even and odd quantities in the neutrino-neutralino mixing matrix enables us to probe the ν_μ–ν_τ and ν_μ–ν_e oscillation amplitudes measured in Super-Kamiokande [2] and the CHOOZ experiment [8] directly in colliders through the measurement of the electron, muon and tau branching ratios of the neutralino LSP [9]. In a detailed analysis, it was found that this testability holds in most of $\tan\beta$ and neutralino mass parameter space, in particular, for the case of the bilinear R-parity violating models [10].

More recently, further development has been made to include the one-loop effect in the determination of the sneutrino VEVs [4,11]. For this, one adds the one-loop correction,

$$V_1 = \frac{1}{64\pi^2}\mathrm{Str}\mathcal{M}^4\left(\ln\frac{\mathcal{M}^2}{Q^2} - \frac{3}{2}\right) , \tag{3}$$

to the scalar potential (2). Then, it is straightforward from the one-loop effective scalar potential to calculate the sneutrino VEVs,

$$\frac{\langle L_i^0\rangle}{\langle H_1^0\rangle} = -\frac{B_i\tan\beta + (m^2_{L_iH_1} + \mu\mu_i) + \Sigma^{(1)}_{L_i}}{m^2_{L_i} + \frac{1}{2}M_Z^2 c_{2\beta} + \Sigma^{(2)}_{L_i}} , \tag{4}$$

where the one-loop correction terms $\Sigma^{(1,2)}_{L_i}$ are given by

$$\Sigma^{(1)}_{L_i} = \left.\frac{\partial V_1}{H_1^{0*}\partial L_i^0}\right|_{L_i^0=0} , \quad \Sigma^{(2)}_{L_i} = \left.\frac{\partial V_1}{L_1^{0*}\partial L_i^0}\right|_{L_i^0=0} , \tag{5}$$

under the condition that the R-parity violating parameters are small, $\mu_i/\mu, \lambda, \lambda' \ll 1$, which is the case with small neutrino masses, $m_\nu \ll M_Z$. The essential step in determining $\Sigma^{(1,2)}$'s is the diagonalization of the mass matrices of neutralinos/neutrinos, charginos/charged leptons and Higgses/sleptons which get mixed due to R-parity violation. This procedure can be done analytically when the R-parity violating parameters are small. The complete analytic formulae for the Σ's are then obtained in [4] including the contributions of all the particles in the MSSM. Having determined the sneutrino VEVs, one obtains the tree mass given by

$$M^\nu_{ij} = \frac{M_Z^2}{F_N}\xi_i\xi_j c_\beta^2 \quad \text{with} \quad F_N = -\frac{M_1 M_2}{M_1 c_W^2 + M_2 s_W^2} - \frac{M_Z^2}{\mu} s_{2\beta} \tag{6}$$

where $\xi_i \equiv \langle L_i^0\rangle/\langle H_1^0\rangle - \mu_i/\mu$, and $M_{1,2}$ are the masses of the neutral gauginos, bino and wino, respectively. Recall that the matrix (6) makes only one neutrino massive.

To obtain the complete neutrino mass eigenvalues and mixing angles, one needs to perform one-loop renormalization of the neutrino/neutralino mass matrix through the general formula,

$$M^{pole}(p^2) = M(Q) + \Pi(p^2) - \frac{1}{2}\left(M(Q)\Sigma(p^2) + \Sigma(p^2)M(Q)\right) \tag{7}$$

where Q is the renormalization scale, and $M(Q)$ is the the $\overline{DR}$ renormalized tree-level mass matrix, Π and Σ are the contributions from one-loop self-energy diagrams. In our case, M is the 7x7 neutrino/neutralino mass matrix consisting of the 3x4 neutrino-neutralino mixing mass matrix M_D and the 4x4 neutralino mass matrix M_N. To find out the 3x3 neutrino mass matrix, usually used is the on-shell renormalization scheme [5,11] in which one works in the tree-level mass basis and rediagonalizes the one-loop corrected 7x7 mass matrix (7). But, as far as only the neutrino sector is concerned, it is more useful to work in the weak basis and obtain the effective neutrino mass matrix by one-step diagonalization [4]. Following this procedure, one finds the neutrino mass matrix;

$$\begin{aligned} M^\nu(p^2) = &-M_D M_N^{-1} M_D^T(Q) + \Pi_n(p^2) \\ &+ M_D M_N^{-1}\Pi_D^T(p^2) + \Pi_D(p^2) M_N^{-1} M_D^T \end{aligned} \tag{8}$$

neglecting the subleading contributions. Here, $\Pi_{n,D}$ are the neutrino-neutrino and neutrino-neutralino one-loop masses. Note that the first term on the right-hand side of Eq. (8) is the tree mass given in Eq. (6). As can be seen from (8), there is no need to calculate the other one-loop terms such as Π_N for neutralino self-energies and Σ's. Furthermore, we can simply take $p^2 = m_\nu^2 = 0$ to calculate the physical neutrino masses and mixing. This should be contrast with the on-shell renormalization scheme where the neutralino masses are also involved in calculating the one-loop renormalized neutrino masses.

Applying the above results to the theories with gauge mediated supersymmetry breaking, one can find various interesting properties [4]. First of all, the one-loop corrections $\Sigma^{(1,2)}_{L_i}$ in Eq. (4) can lead to a drastic change in the sneutrino VEVs. This effect is magnified in the parameter ranges where a partial cancellation between the two quantities, $(m^2_{L_iH_1} + \mu\mu_i)$ and $B_i \tan\beta$, occurs. In certain cases, it can even change the order of magnitudes of the neutrino mass eigenvalues. The most interesting question is again what kind of realistic neutrino mass matrices accounting for the atmospheric and solar neutrino oscillations can be obtained. In the bilinear models, it turns out that only realizable is the small mixing MSW solution to the solar neutrino problem with $\tan\beta \geq 20$. In the trilinear models, one has more freedom and thus more solutions. For instance, the small mixing MSW solution can be obtained even for small $\tan\beta$. An interesting aspect is that the bi-maximal mixing solution to the atmospheric and solar neutrino problems can also be realized with small $\tan\beta$.

Finally, we would like to emphasize that the desirable neutrino mass matrices with R-parity violation arise without fine-tuning of parameters given the overall smallness of R-parity violating parameters, $\mu_i/\mu, \lambda$ and λ'. This smallness may be a consequence of a certain flavor symmetry responsible for the quark and lepton mass hierarchies, such as horizontal U(1) symmetry [12].

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